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Utilization of Electrical Energy to Enhance Performance of Solid Propellant Guns

Gloria P. Wren
William F. Oberle
Walter F. Morrison

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Although the ETC propulsion system is often implemented with a novel propellant formulation to exploit the potential for high volumetric energy density and low molecular weight products, the introduction of an electrically generated plasma into a solid propellant has been proposed and, in fact, initially tested. Proponents of introducing plasma energy into the breech of a traditional solid propellant gun expect the plasma to serve two functions: 1) perform as the igniter for the solid propellant, and 2) increase the muzzle energy by providing an additional energy source to the propulsive gases. In this report, the feasibility of the second potential role of the electrically generated plasma in a solid propellant gun is explored theoretically. Estimates are made of electrical energy required to reach specific performance goals in a 60-mm gun.

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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1. INTRODUCTION

In the electrothermal-chemical (ETC) gun, an electrically generated high-pressure, high-temperature plasma interacts with a propellant (working fluid) in the combustion chamber to provide propulsive gases for the projectile. As shown in Figure 1, an ETC system consists of a power supply, pulse-forming network, switches, the plasma capillary, the combustion chamber in which the plasma and propellant interact, and the gun tube/projectile. A number of propellants have been proposed for the ETC gun including liquids, gels, slurries, and solids.

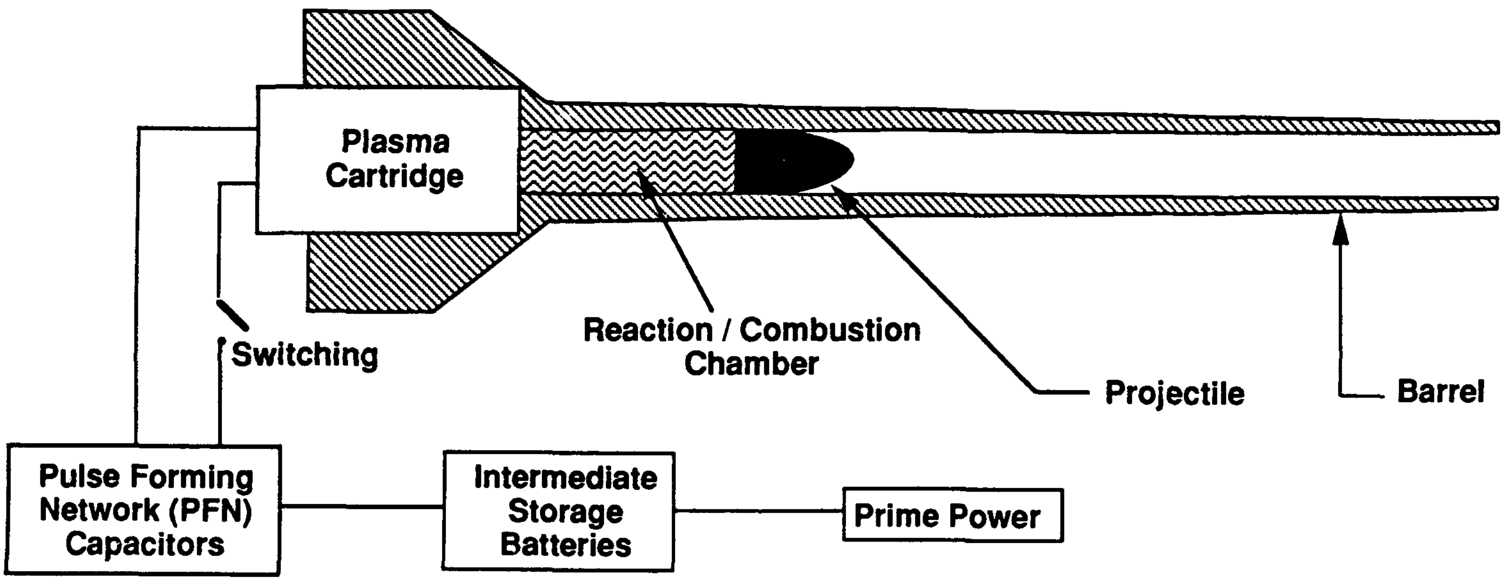

Figure 1. Schematic of ETC Gun.

Although the ETC propulsion system is often implemented with a novel propellant formulation to exploit the potential for high volumetric energy density and low molecular weight products, the introduction of an electrically generated plasma into a solid propellant has been proposed and, in fact, initially tested (SOREQ 1991). Proponents of introducing plasma energy into the breech of a traditional solid propellant gun expect the plasma to serve two functions: 1) perform as the igniter for the solid propellant, and 2) increase the projectile muzzle kinetic energy (KE) by providing an additional energy source to the propulsive gases. In this report, the feasibility of the second potential role of the electrically generated plasma in a solid propellant gun is explored.

In the implementation discussed in this report, electrical energy (EE) in the form of a plasma is introduced into the breech of the gun at and after the time of maximum chamber pressure. In this scenario, the electrical energy serves to maintain the maximum breech pressure and, hence, the space-mean pressure and the base pressure for some time period after maximum chamber pressure due to the solid propellant alone. It is further assumed, in this report, that the solid propellant is ignited conventionally. Finally, it is also assumed that ideal "lossless" conditions exist after maximum breech pressure and that the electrical pulse can be appropriately shaped to deliver the desired pulse shape to maintain maximum breech pressure. ("Lossless" is interpreted to mean that no additional losses will occur over the baseline calculation.) It has been shown (Morrison et al., to be published) that traditional pressure gradient relationships are appropriate for ETC gun modeling. Thus, using the Lagrange gradient (Corner 1950) and isentropic flow relations, it is possible to derive a closed-form solution for the amount of electrical energy required after maximum pressure to attain various performance regimes in terms of maximum pressure and muzzle velocity, as well as to determine the percentage of electrical energy converted to projectile kinetic energy.

2. BASELINE SOLID PROPELLANT ONLY RESULTS

The gun specification used for the solid propellant only baseline case is given in Table 1. In the table, the propellant L/D is the length to diameter ratio of the propellant grains, and D/Dp is the ratio of the outside diameter to the perf diameter. The propellant mass and web are determined by optimizing muzzle velocity with the maximum breech pressure constraint using the lumped parameter interior ballistic code IBHVG2 (Anderson and Fickie 1987; Baer 1991).

The baseline optimal muzzle velocity computed by IBHVG2 for the totally solid propellant gun is 1,654 m/s. The total chemical energy available from the solid propellant is 8,303,941 J. Conditions at muzzle exit and at maximum chamber pressure (optimized solid) needed in the calculation are shown in Table 2.

3. MAXIMUM PERFORMANCE ESTIMATES

In order to provide an upper bound on gun performance in muzzle velocity or kinetic energy, given a breech pressure constraint, it is assumed that electrical energy is added to the breech starting at the time of maximum chamber pressure and continued until projectile exit to maintain the chamber, and hence the

Table 1. Gun Parameters

Maximum Projectile Travel	3.864 m
Chamber Volume	2,130 cm^3
Bore Diameter	60 mm
Propellant Mass	1.851 kg
Propellant	M30, 7-perf
Propellant Geometry	L/D = 2.095 D/Dp = 11.077
Maximum Chamber Pressure	475 MPa
Projectile Mass	1.354 kg

Table 2. Conditions at Muzzle Exit and Maximum Chamber Pressure Using M30, 7-Perf.

Muzzle Exit	Maximum Chamber Pressure
Projectile Velocity = 1,654 m/s Projectile KE = 1,851,011 J Gas KE = 908,601 J Gas Internal Energy = 5,074,535 J Losses = 469,794 J Total Chemical Energy = 8,303,941 J	Projectile Travel: 0.4111 m Projectile Velocity = 670 m/s Base Pressure: 288 MPa

base, pressure as shown in Figure 2. Figure 2 also shows the solid-propellant-only breech pressure history. An energy balance at the muzzle is used to determine both the quantity of electrical energy required and the percentage transferred to projectile kinetic energy. The gun specifications are given in Table 1.

The calculation now proceeds by assuming that electrical energy is added to the breech to maintain a projectile base pressure of 288 MPa (the value at maximum breech pressure) for the remainder of the projectile travel. It is assumed that the tube can withstand the base pressure.

The area of bore is $\pi(3\ cm)^2$ or $0.0009\pi m^2$. The projectile kinetic energy with constant base pressure of 288 MPa for the travel after maximum breech pressure, P_{max}, is

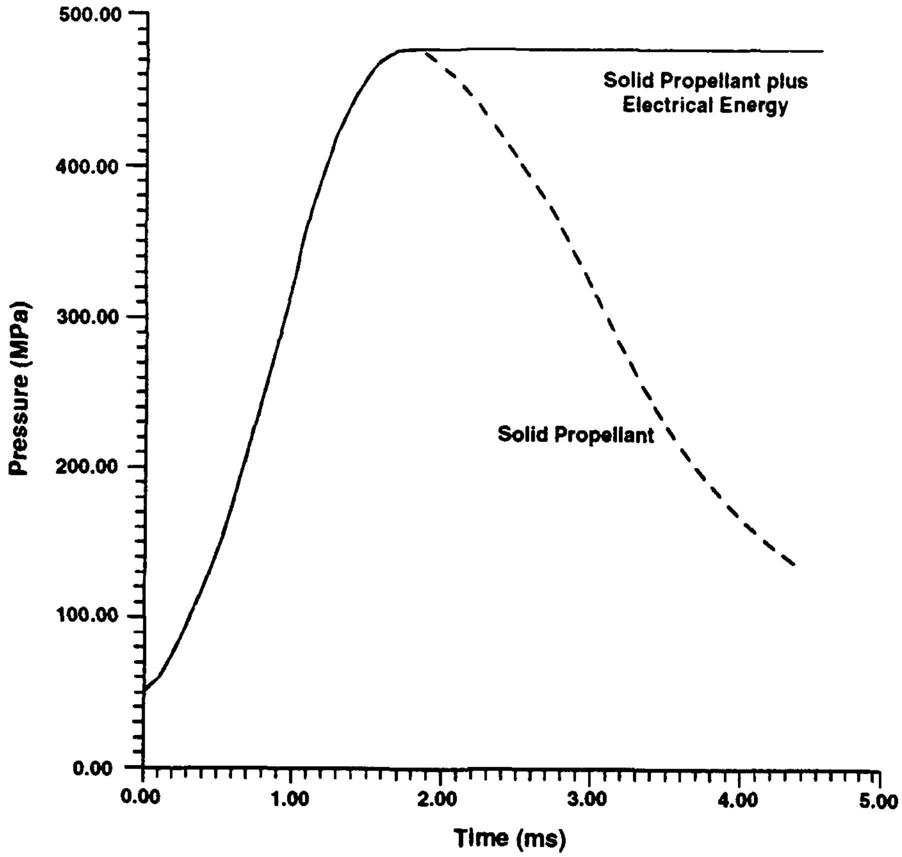

Figure 2. Chamber Pressure Obtained by Addition of Electrical Energy From Maximum Breech Pressure Until Muzzle Exit, Compared to the Solid-Propellant-Only Breech Pressure History.

$$\text{Projectile KE} = P_{base} * A_{bore} * (X_m - X_p)$$

$$\text{Projectile KE} = (288 \cdot 10^6 \text{ Pa}) \cdot 0.0009\pi \text{m}^2 \cdot (3.864 \text{ m} - 0.4111 \text{ m})$$

$$= 288 \cdot 10^6 \frac{\text{kg}}{\text{s}^2 \cdot \text{m}} \cdot 0.0009\pi \text{m}^2 \cdot 3.4529 \text{ m}$$

$$= 2{,}811{,}700 \text{ J}, \tag{1}$$

where X_m and X_p are projectile position at muzzle exit and maximum pressure, respectively. Projectile kinetic energy at P_{max} = 1/2 (1.354 kg) (670 m/s)^2 = 303,905 J. The total projectile kinetic energy is then (2,811,700 J + 303,905 J) = 3,115,605 J, which gives a projectile muzzle velocity of 2,145 m/s. Hence, the maximum increase in muzzle velocity over the baseline of 1,654 m/s is 30%, equivalent to a 68% increase in projectile kinetic energy.

In order to estimate the amount of electrical energy required to obtain the muzzle velocity of 2,145 m/s, an energy balance is calculated at muzzle exit conditions. The projectile kinetic energy from above is 3,115,605 J. The gas kinetic energy is calculated from the Lagrange pressure gradient relationships, that is, gas kinetic energy = 1/3 C/M KE_p where C/M is the ratio of the mass of the charge to the mass of the projectile, and KE_p is the kinetic energy of the projectile. Thus, substituting,

$$\text{Gas KE} = \frac{1}{3}\frac{(1.851\ \text{kg} + .15\ \text{kg})}{1.354\ \text{kg}}(3{,}115{,}605\ \text{J}) = 1{,}534{,}792\ \text{J}\ .$$

It is noted that the charge mass consists of 1.851 kg of main charge and 0.15 kg of black powder igniter.

The gas internal energy is given by

$$\text{Gas Internal Energy} = \frac{\bar{P}V}{\gamma - 1}\ . \tag{2}$$

Using the Lagrange gradient for the space-mean pressure,

$$\bar{P} = \frac{1 + \frac{1}{3}\frac{C}{M}}{1 + \frac{1}{2}\frac{C}{M}} P_{breech} = \frac{1 + \frac{1}{3}(1.478)}{1 + \frac{1}{2}(1.478)} 475\ \text{MPa} = 408\ \text{MPa}\ . \tag{3}$$

The total volume is the initial chamber volume plus the volume in the tube, or

$$V = .00213\ \text{m}^3 + \pi(0.03\ \text{m})^2(3.864\ \text{m}) = 0.013\ \text{m}^3\ .$$

Therefore, the gas internal energy at muzzle exit is then given by

$$\text{Gas Internal Energy} = \frac{408 \cdot 10^6 \cdot 0.013}{1.25 - 1} = 21{,}216{,}000\ \text{J}.$$

Thus, at muzzle exit, the total energy is the sum of projectile kinetic energy, gas kinetic energy, gas internal energy and losses, or 26,336,354 J. The electrical energy required is the difference between total energy and chemical energy, or

$$\text{EE required} = 26{,}336{,}354 - 8{,}303{,}941 = 18{,}032{,}413 \text{ J} \approx 18 \text{ MJ} .$$

The percentage of electrical energy delivered to the projectile is

$$\frac{\Delta \text{ Projectile KE}}{\text{EE added}} = \frac{\text{Energy with EE} - \text{Energy w/o EE (IBHVG2)}}{\text{Electrical Energy}}$$

$$= \frac{3{,}115{,}605 \text{ J} - 1{,}851{,}011 \text{ J}}{18{,}032{,}413 \text{ J}} = 7\% . \tag{4}$$

Thus, although 18 MJ of electrical energy is required to increase muzzle energy 30% over the baseline of zero electrical energy, only 7% of the electrical energy is translated into projectile kinetic energy.

4. PERFORMANCE ENHANCEMENT WITH INCREMENTAL ELECTRICAL ENERGY ADDITION

A pulse power system which will deliver 18 MJ of energy in ballistic timescales is not weaponizable for tactical Army applications at present. In addition, systems burdens will result from gun tubes and recoil systems which must be capable of withstanding maximum projectile base pressure for the entire tube length. Excessive projectile base pressure at muzzle exit is also of concern due to muzzle flash, blast, and signature. Thus, it is of interest to determine performance enhancement by adding electrical energy to the breech after maximum pressure for a given portion of the projectile travel as shown in Figure 3. It is also of interest to determine the percentage of electrical energy converted to projectile kinetic energy as a function of projectile travel at which electrical energy is terminated.

As in the previous maximum performance case, the solid-propellant-only, optimized, IBHVG2 calculation defines the conditions up to maximum chamber pressure as shown in Table 2. The muzzle exit conditions in Table 2 define the baseline, optimized solid propellant case. It is then assumed that a constant breech pressure of 475 MPa is maintained by electrical energy addition until X_T, the projectile position at termination of electrical energy. After the projectile position at X_T, the gas expands from X_T to X_m = 3.864 m, where X_m is projectile position at muzzle exit, subject to the following assumptions: 1) adiabatic expansion (no losses), 2) isentropic flow relation along the same adiabatic: $\bar{P}V^{\gamma} = K$, a constant, where $\bar{P}$ is the space-mean pressure, V is the volume, and γ the ratio of specific heats. The

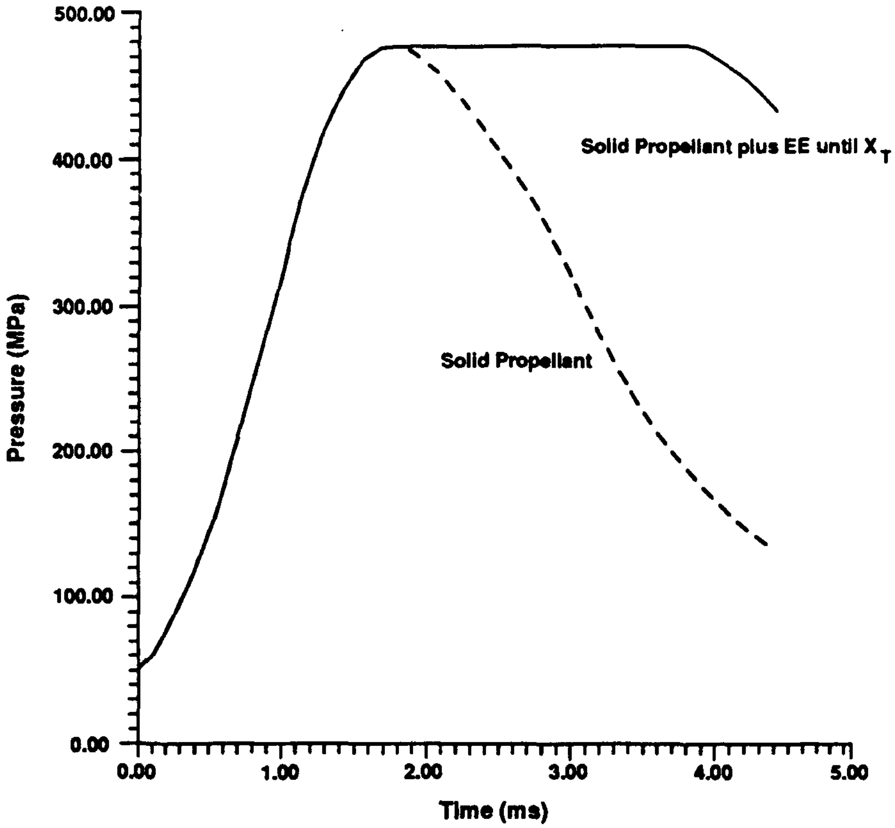

Figure 3. Electrical Energy Addition From Maximum Chamber Pressure Until a Given Projectile Position.

relationship between projectile base pressure and space-mean pressure is given by the Lagrange pressure gradient relationship,

$$P_{base} = \frac{1}{\left(1 + \frac{1}{3}\frac{C}{M}\right)}\bar{P} = \frac{1}{1 + \frac{1}{3}(1.478)}\bar{P} = \alpha\bar{P} = 0.67\,\bar{P}, \qquad (5)$$

since the charge mass is 2.001 kg and the projectile mass is 1.354 kg.

The projectile kinetic energy during the gas expansion is given by

$$\text{Projectile KE} = \int_{X_T}^{X_m} P_{base}\,A(x)\,dx = \int_{X_T}^{X_m} \alpha\bar{P}(x)\,A(x)\,dx \qquad (6)$$

using Equation 5 to express P_{base}. The space-mean pressure at any travel, $\bar{P}(x)$, is related to the space-mean pressure at the termination of electrical energy through the isentropic relation. That is,

$$\bar{P}_T(V_T - \eta C)^\gamma = \bar{P}(x)[V(x) - \eta C]^\gamma, \tag{7}$$

where the subscript T denotes conditions at the termination of electrical energy. Substituting for volume at constant bore area, A,

$$\bar{P}_T(AX_T - \eta C)^\gamma = \bar{P}(x)[AX - \eta C]^\gamma , \tag{8}$$

or

$$\bar{P}(x) = \frac{(AX_T - \eta C)^\gamma}{(AX - \eta C)^\gamma}\bar{P}_T . \tag{9}$$

Thus, the projectile kinetic energy during expansion is given by

$$\begin{aligned}
\text{Projectile KE} &= \int_{X_T}^{X_m} \alpha\bar{P}(x)A\,dx \\
&= \alpha A \int_{X_T}^{X_m} \frac{(AX_T - \eta C)^\gamma}{(AX - \eta C)^\gamma}\bar{P}_T\,dx \\
&= \alpha(AX_T - \eta C)^\gamma \bar{P}_T \int_{X_T}^{X_m} \frac{1}{(AX - \eta C)^\gamma}\,dx \\
&= \alpha(AX_T - \eta C)^\gamma \bar{P}_T \frac{(AX - \eta C)^{1-\gamma}}{A(1-\gamma)}\Big|_{X_T}^{X_m} \\
&= \alpha(AX_T - \eta C)^\gamma \frac{\bar{P}_T}{(1-\gamma)}\left[(AX_M - \eta C)^{1-\gamma} - (AX_T - \eta C)^{1-\gamma}\right].
\end{aligned} \tag{10}$$

It is noted that, in this analysis, all solid propellant must be consumed by X_T to satisfy the assumption of isentropic expansion. Otherwise, the treatment of the expansion regime must consider the presence of solid propellant particles.

By way of illustration of the above analysis, to determine the effect of adding electrical energy after P_{max}, assume electrical energy is terminated and that all solid propellant is consumed by $X_T = 2.0$ m, a valid condition based on IBHVG2 results. At the projectile position, X_{max}, on reaching maximum chamber pressure, the projectile velocity is 670 m/s and the projectile kinetic energy is 303,905 J. From X_{max} to X_T, the projectile kinetic energy is = $288 \cdot 10^6$ Pa $\cdot$ $0.0009\pi m^2$ $\cdot$ (2.0 m − 0.4111 m), or 1,293,842 J. From X_T to X_m the projectile kinetic energy is given by Equation 10 to be 790,065 J. Thus, the total kinetic energy of the projectile is 303,905 + 1,293,842 + 790,065 = 2,387,813 J. The muzzle velocity is then calculated from the total kinetic energy to be 1,878 m/s. The increase in muzzle velocity over the baseline of 1,654 m/s is 13.5%, which corresponds to a projectile kinetic energy increase of 29%.

The amount of electrical energy required for the increase in muzzle velocity is based on the energy balance at muzzle exit. The projectile kinetic energy is 2,387,813 J. The gas kinetic energy using the Lagrange relationship is

$$\text{Gas KE} = \frac{1}{3}\frac{C}{M}KE_p = \frac{1}{3}(1.478)(2{,}387{,}813\ \text{J}) = 1{,}176{,}271\ \text{J}\,.$$

The gas internal energy = $\frac{\bar{P}V}{\gamma - 1}$ where

$$\bar{P}(X_m) = \frac{(AX_T - \eta C)^\gamma}{(AX_m\ \eta C)^\gamma}\bar{P}_T = 131\ \text{MPa}$$

in a volume of .023 m^3 is

$$\text{Gas Internal Energy} = \frac{\bar{P}(X_M) \cdot 10^6\,\text{Pa} \cdot 0.013\ m^3}{1.25 - 1} = 6{,}836{,}711\ \text{J}\,.$$

The total energy required is the sum of projectile kinetic energy, gas kinetic energy, gas internal energy and losses or 10,870,589 J.

The electrical energy needed is the total energy minus the chemical energy (IBHVG2), or 2.6 MJ. The percentage of electrical energy delivered to projectile is

$$\frac{\Delta \text{ Projectile KE}}{\text{EE}} = \frac{\text{Energy with EE} \; - \; \text{Energy w/o EE (IBHVG2)}}{\text{EE}}$$

$$= \frac{2{,}387{,}813 \text{ J} - 1{,}851{,}011 \text{ J}}{2{,}568{,}430 \text{ J}}$$

$$= 20.9\% \; .$$

Thus, supplementing the chemical energy with 2.6 MJ of electrical energy for a small amount of projectile travel after maximum pressure results in a 13.5% increase in projectile velocity over optimized solid propellant performance and an electrical energy efficiency of about 21%.

In order to examine the effect of adding electrical energy until an arbitrary projectile position is reached, the model described above was encoded into a computer program for ease of use. Since the model assumptions are that isentropic flow takes place after the period of electrical energy addition, it is essential that solid propellant burning be complete at X_T. The IBHVG2 calculation for the optimized solid propellant charge shows that the solid propellant is consumed by approximately 2.0 m of projectile travel. Thus, the results of electrical energy addition to maintain the maximum chamber pressure until a projectile travel of 2.0 m, 2.5 m, 3.0 m, and 3.864 m are shown in Figures 4–7.

In Figure 4, electrical energy added to maintain maximum chamber pressure is shown as a function of projectile position at electrical energy termination. Since the gas internal energy is the major portion of the system total energy, and internal energy is directly related to volume in a constant area tube, the required electrical energy appears as approximately linear.

In Figure 5, muzzle velocity vs. projectile position at electrical energy termination is shown. The projectile velocity percentage increase over the baseline is shown in Figure 6. Muzzle velocity does increase with electrical energy addition; however, the relationship is not linear. As shown in Figure 7, projectile kinetic energy increases more slowly as electrical energy is added for longer projectile travel. This is due to the fact that the internal energy of the gas is increasing at the rate of four times the volume increase (since γ is 1.25). Figure 8 shows the percentage increase in projectile kinetic energy and reflects the inefficient use of electrical energy added late in the interior ballistic event.

The percentage of electrical energy transferred to the projectile kinetic energy vs. projectile position at electrical energy termination is shown in Figure 9. As expected, the highest electrical energy efficiency

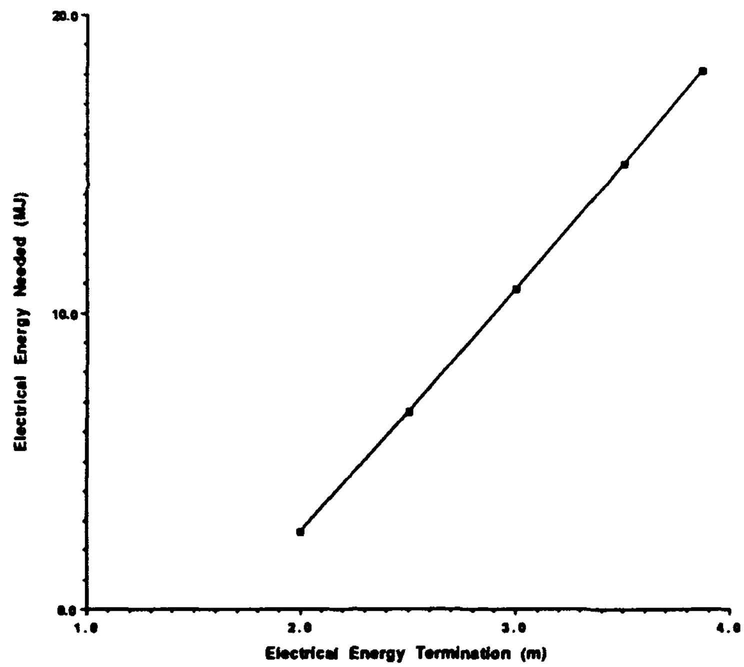

Figure 4. Electrical Energy Addition To Maintain Maximum Chamber Pressure vs. Projectile Position at Electrical Energy Termination.

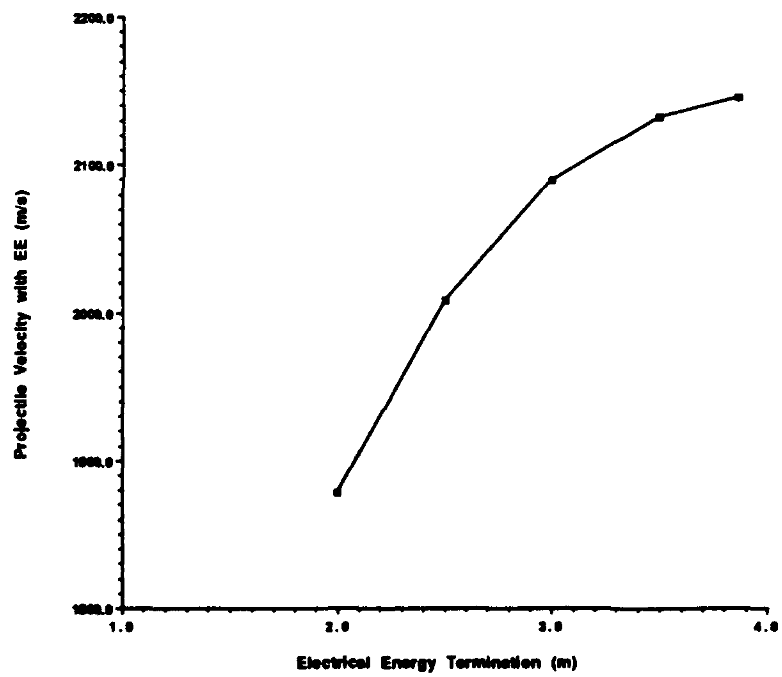

Figure 5. Muzzle Velocity vs. Projectile Position at Electrical Energy Termination.

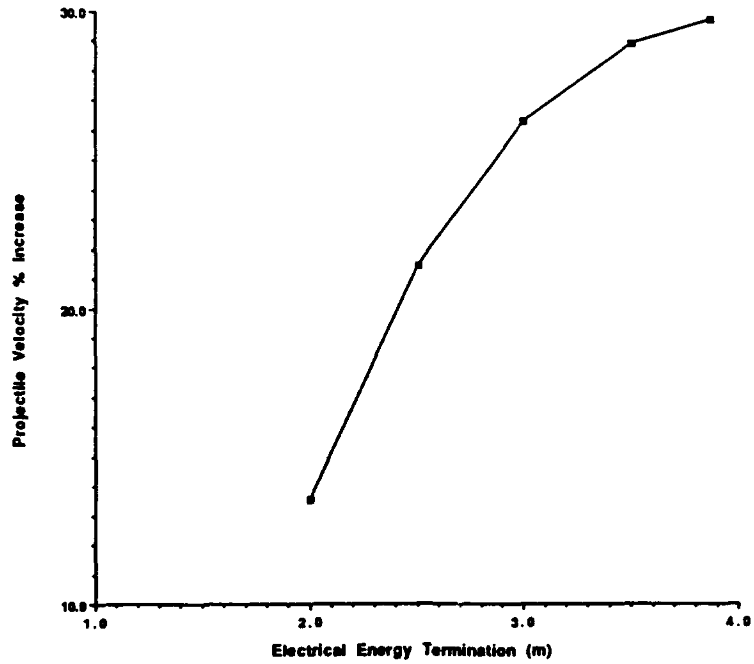

Figure 6. Projectile Muzzle Velocity Percentage Increase vs. Projectile Position at Electrical Energy Termination.

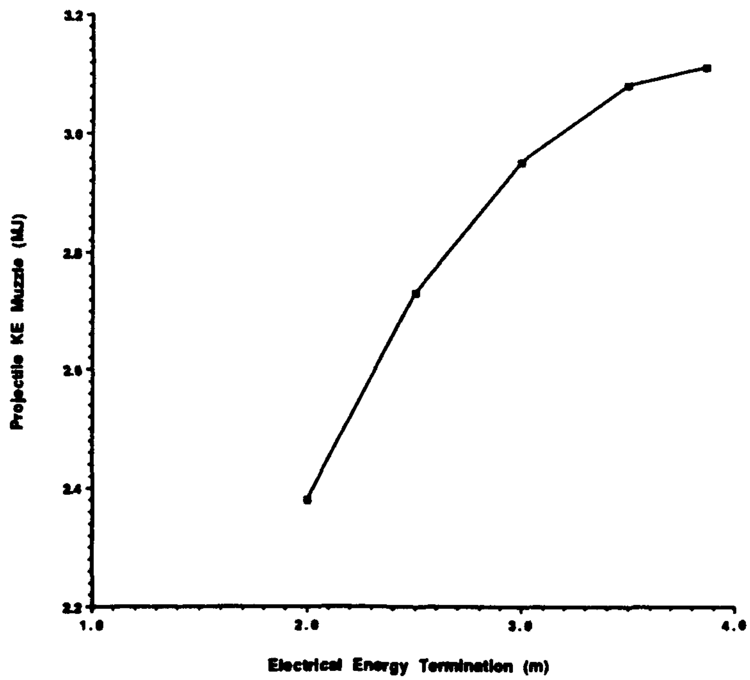

Figure 7. Projectile Kinetic Energy vs. Projectile Position at Electrical Energy Termination.

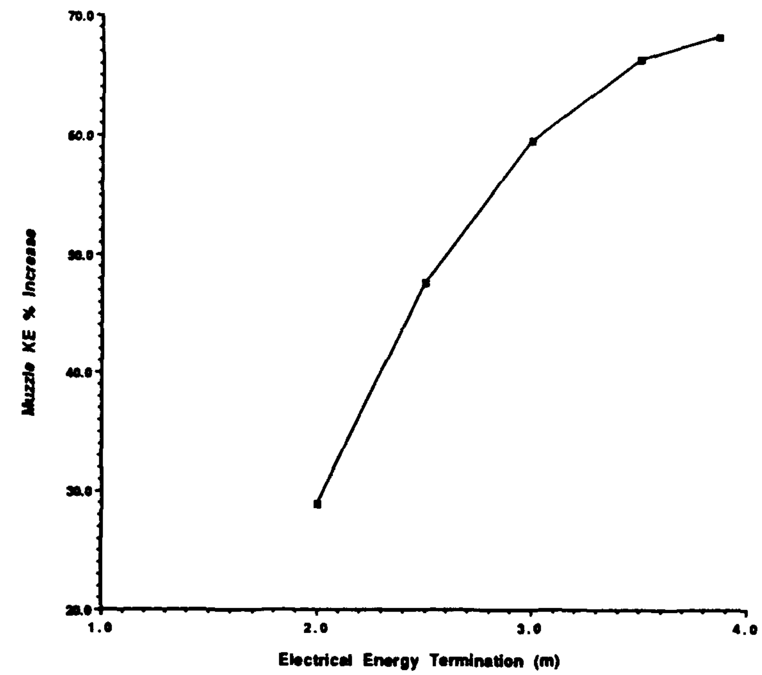

Figure 8. Projectile Kinetic Energy Percentage Increase vs. Projectile Position at Electrical Energy Termination.

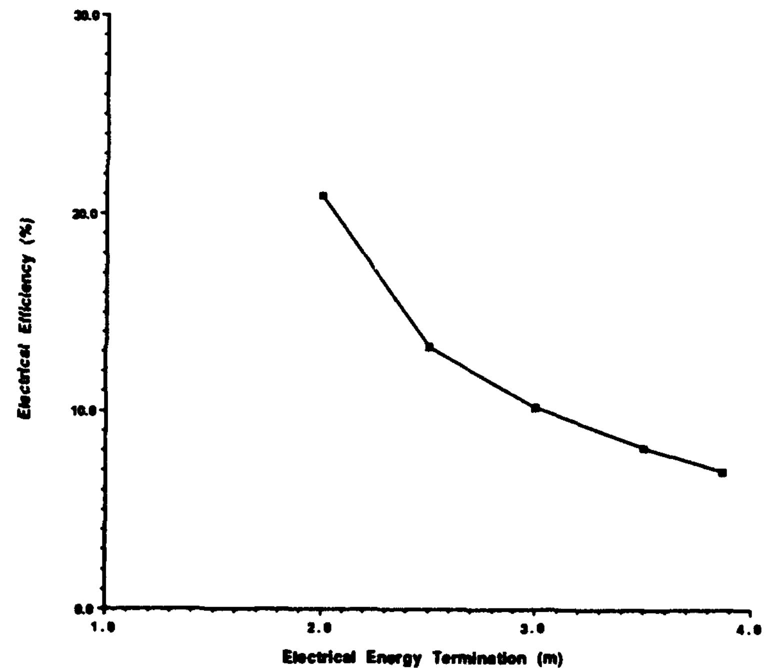

Figure 9. Electrical Energy Efficiency vs. Projectile Position at Electrical Energy Termination.

occurs when electrical energy is terminated early in the projectile travel. The longer time for gas expansion allows more energy to be translated to the projectile. It is seen that electrical energy efficiency drops rapidly with longer electrical energy addition. The most significant portion of available energy resides as internal energy of the gas in the rapidly expanding volume. In an actual gun, the finite time for the breech addition of electrical energy to affect projectile base pressure will result in efficiencies which are even poorer.

5. TEMPERATURE

The Nobel-Abel equation-of-state for the gas is

$$\bar{P}(V - \eta C) = nRT$$

where V is the volume of gas, η the co-volume, n the number of moles of gas, R the universal gas constant, and T the temperature. Since the electrical energy will add a negligible amount of mass and $\bar{P}$ and n are constants after all-burnt if the maximum breech pressure is maintained by electrical energy addition, the average gas temperature is directly related to volume by

$$T = \frac{\bar{P}(V - \eta C)}{nR} .$$

The main charge has a molecular weight of 23.242 g/mol, giving 79.64 moles of gas.

Thus, if maximum breech pressure is maintained until muzzle exit, the average gas temperature is 6,242 K. The average gas temperature at the projectile position corresponding to electrical energy termination is shown in Figure 10. However, local gas temperatures are expected to be even higher since the plasma temperature is 10,000–20,000 K. Thus, in the case of substantial performance increase, solid propellant ETC guns will require novel approaches to thermal management.

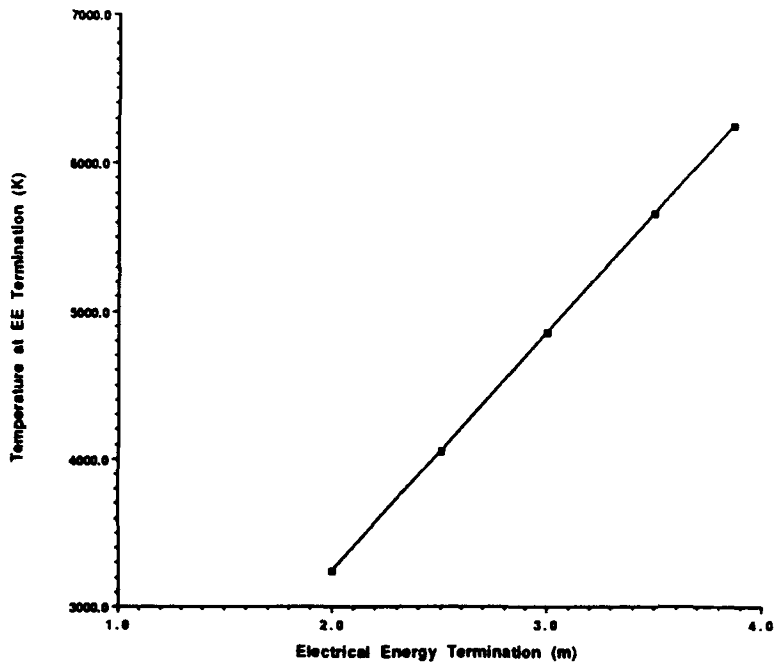

Figure 10. Average Gas Temperature vs. Projectile Position at Electrical Energy Termination.

6. CONCLUSIONS

Analytic solution of the thermodynamic and energy equations describing a solid propellant electrothermal-chemical gun (SPETC) operating under ideal conditions provides an estimate of performance, performance increase over solid propellant alone, efficiency, electrical energy requirements, and gas temperatures. The analytic solution utilizes a traditional, lumped parameter, solid propellant simulation for comparison.

The energy budget for a particular gun is dependent on geometry, solid propellant parameters, and operating conditions. However, it appears that under the ideal conditions examined in this study of a 60-mm gun, the breech addition of electrical energy to enhance the chemical energy of the solid propellant can result in significant muzzle velocity increases of up to 30% in the 60-mm system. However, the quantity of electrical energy required is large (18 MJ for a 30% muzzle velocity increase) and potential system burdens are great. More modest increases in muzzle velocity appear possible with less electrical energy. Thus, significant performance enhancement through the breech addition of electrical energy appears to be attainable only at considerable system burdens in terms of power supply, temperature effects, tube pressure, and muzzle blast.

Thus, the advantage of SPETC guns may lie in the unique, but unproven, potential of electrical energy to ignite novel propellants, reduce temperature sensitivity effects of solid propellants, and broaden the scope of charge design. For example, consolidated charges may be able to be implemented in SPETC guns. In these scenarios, electrical energy requirements are small since the electrical energy is not used primarily to supplement the chemical energy of the solid propellant. The analysis explored in this report suggests that research in SPETC guns should include the role of electrical energy in initiating the interior ballistic process rather than simply as an additional energy source.

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APPENDIX A:

SAMPLE INPUT AND OUTPUT

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Sample Input for ETSOLID.FOR

```
2.001     WTCH=CHARGE MASS (KG) 1.851+0.15, INCLUDING IGNITER
1.354     WTPR=PROJECTILE MASS (KG)
0.06      DIAM=BORE DIAMETER (M)
1.25      GAM=GAMMA
0.001048 COVOL=COVOLUME (M^3/KG)
0.023242 RMOLWT=MOLECULAR WEIGHT (KG/MOL)
0.00213  CHVOL=CHAMBER VOLUME (M^3)
3.864     XM=TRAVEL (M)
475.      PMAX=MAX CHAMBER PRESSURE (MPA) *** CONDITIONS AT PMAX
288.       PBASE=BASE  PRESSURE  AT  PMAX  (MPA) [USE 0.0 IF NOT
KNOWN]
670.      PRVEL1=PROJECTILE VELOCITY AT PMAX (M/S)
0.4111    PROJECTILE TRAVEL AT PMAX (M)
1654.0    PROJECTILE VELOCITY AT MUZZLE (M/S)  ***CONDITIONS  AT
MUZZLE
8303941. CHEMEN=CHEMICAL ENERGY AVAILABLE (J)
469794.  LOSSES (J)
2.0       XEND=POINT CLOSEST TO MUZZLE FOR EE TERMINATION (M)
```

** ADDITION OF ELECTRICAL ENERGY TO SOLID PROPELLANT **

```
ELEC ENERGY TERMINATION POINT (M) =    3.8640
TEMPERATURE AT EE TERMINATION (K) =    6241.9
PROJECTILE KE MUZZLE (J) =       3115605.0
GAS KE MUZZLE (J) =       1534792.0
GAS INTERNAL ENERGY (J) =       21291430.0
PROJECTILE VELOCITY WITH EE (M/S) =    2145.24
PROJECTILE VELOCITY % INCREASE =       29.7
MUZZLE KE % INCREASE =       68.2
ELECTRICAL ENERGY NEEDED (MJ) =      18.11
ELECTRICAL EFFICIENCY (%) =       7.0

ELEC ENERGY TERMINATION POINT (M) =    3.5000
TEMPERATURE AT EE TERMINATION (K) =    5655.6
PROJECTILE KE MUZZLE (J) =       3079216.0
GAS KE MUZZLE (J) =       1516867.0
GAS INTERNAL ENERGY (J) =       18235340.0
PROJECTILE VELOCITY WITH EE (M/S) =    2132.68
PROJECTILE VELOCITY % INCREASE =       28.9
MUZZLE KE % INCREASE =       66.3
ELECTRICAL ENERGY NEEDED (MJ) =      15.00
ELECTRICAL EFFICIENCY (%) =       8.2

ELEC ENERGY TERMINATION POINT (M) =    3.0000
TEMPERATURE AT EE TERMINATION (K) =    4850.4
PROJECTILE KE MUZZLE (J) =       2954810.0
GAS KE MUZZLE (J) =       1455582.0
GAS INTERNAL ENERGY (J) =       14201690.0
PROJECTILE VELOCITY WITH EE (M/S) =    2089.15
PROJECTILE VELOCITY % INCREASE =       26.3
MUZZLE KE % INCREASE =       59.5
ELECTRICAL ENERGY NEEDED (MJ) =      10.78
ELECTRICAL EFFICIENCY (%) =       10.2

ELEC ENERGY TERMINATION POINT (M) =    2.5000
TEMPERATURE AT EE TERMINATION (K) =    4045.1
PROJECTILE KE MUZZLE (J) =       2731307.0
GAS KE MUZZLE (J) =       1345481.0
GAS INTERNAL ENERGY (J) =       10386770.0
PROJECTILE VELOCITY WITH EE (M/S) =    2008.59
PROJECTILE VELOCITY % INCREASE =       21.4
MUZZLE KE % INCREASE =       47.5
ELECTRICAL ENERGY NEEDED (MJ) =      6.63
ELECTRICAL EFFICIENCY (%) =       13.3

ELEC ENERGY TERMINATION POINT (M) =    2.0000
TEMPERATURE AT EE TERMINATION (K) =    3239.8
PROJECTILE KE MUZZLE (J) =       2387813.0
GAS KE MUZZLE (J) =       1176271.0
GAS INTERNAL ENERGY (J) =       6836711.0
PROJECTILE VELOCITY WITH EE (M/S) =    1878.04
PROJECTILE VELOCITY % INCREASE =       13.5
MUZZLE KE % INCREASE =       28.9
ELECTRICAL ENERGY NEEDED (MJ) =      2.57
ELECTRICAL EFFICIENCY (%) =       20.9
```

APPENDIX B:

SOURCE CODE LISTING

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```
      PROGRAM ETSOLID
C
      IMPLICIT REAL (A-H,O-Z)
      CHARACTER*20 FILEIN,FILOUT
C
C USES AS INPUT CONDITIONS IN SOLID PROPELLANT SIMULATION
C THEN DETERMINES INCREASE IN PERFORMANCE BY ADDITION OF
C ELECTRICAL ENERGY TO MAINTAIN MAX CHAMBER PRESSURE
C FOR SOME DISTANCE DOWNTUBE
C
      PI=2.*ASIN(1.0)
C
C  INITIAL CONDITIONS (KG,M,S)
C
      WRITE(*,*)' PLEASE NAME INPUT FILE:   '
      READ(*,10) FILEIN
      WRITE(*,*)' PLEASE NAME OUTPUT FILE:  '
      READ(*,10) FILOUT
   10 FORMAT(A20)
      OPEN(12,FILE=FILEIN)
      OPEN(14,FILE=FILOUT)
C WTCH=CHARGE MASS (KG)
C WTPR=PROJECTILE MASS (KG)
C DIA=BORE DIAMETER (M)
C GAM=RATIO OF SPECIFIC HEATS
C COVOL=COVOLUME (KG/M^3)
C RMOLWT=MOLECULAR WEIGHT
C CHVOL=CHAMBER VOLUME
C XM=TRAVEL (M)
      READ(12,*) WTCH
      READ(12,*) WTPR
      ALPHA=1./(1.+(1./3.)*WTCH/WTPR)
      READ(12,*) DIA
      AREA=PI*0.5*DIA*0.5*DIA
      READ(12,*) GAM
      READ(12,*) COVOL
      VOLM=COVOL*WTCH
      READ(12,*) RMOLWT
      RNMOL=WTCH/RMOLWT
      R=8.314
      READ(12,*) CHVOL
      READ(12,*) XM
C
C  CONDITIONS AT PMAX
C
C PMAX=MAXIMUM CHAMBER PRESSURE
C  PBASE=PROJECTILE  BASE PRESSURE AT PMAX--NOTE: USE 0.0 IF
NOT KNOWN
C PRVEL1=PROJECTILE VELOCITY AT MAX CHAMBER PRESSURE
C PRKE1=PROJECTILE KINETIC ENERGY AT MAX CHAMBER PRESSURE
C XMAX=PROJECTILE TRAVEL AT MAX CHAMBER PRESSURE
      READ(12,*) PMAX
      READ(12,*) PBASE
      CM=WTCH/WTPR
      PBART=((1.+(1./3.)*CM)/(1.+(1./2.)*CM))*PMAX
      READ(12,*) PRVEL1
      PRKE1=0.5*WTPR*PRVEL1*PRVEL1
      READ(12,*) XMAX
```

```
C
C  CONDITIONS AT MUZZLE WITH SOLID PROPELLANT
C
C PRVELS=PROJECTILE VELOCITY AT MUZZLE WITH SOLID PROPELLANT
ALONE
C  CHEMEN=CHEMICAL ENERGY  AVAILABLE  (J)  (NOTE:  INCLUDING
IGNITER)
C XEND=LAST EE TERMINATION POINT TO CONSIDER (NOTE: ALL
C      SOLID PROPELLANT MUST BE CONSUMED)
       READ(12,*) PRVELS
       PRKES=0.5*WTPR*PRVELS*PRVELS
       VOLTOT=CHVOL+AREA*XM
       READ(12,*) CHEMEN
       READ(12,*) RLOSS
       READ(12,*) XEND
C
C TERMINATION POINT OF ELECTRICAL ENERGY BEGINS AT MUZZLE
C
       XT=XM
       ISTEP=INT(2.*(XM-XEND)+1.)+1
       WRITE(14,200)
       DO 100 I=1,ISTEP
C
C  TEMPERATURE AT EE TERMINATION (K)
C
        TEMP=(PBART*1.E+6*(CHVOL+AREA*XT                        -
COVOL*WTCH))/(RNMOL*R)
C
C  FROM XMAX TO XT
C
C  IF PBASE IS NOT GIVEN, FIND THE VALUE
        IF (PBASE .LT. 0.1) PBASE=(1./(1.+(1./3.)*CM))*PBART
        PRKE2=PBASE*1.E+6*AREA*(XT-XMAX)
C
C  FROM XT TO XM
C
        IF ( ABS(XM-XT) .LE. 0.01) THEN
           PRKE3=0.0
        ELSE
           TERM1=(AREA*XM-VOLM)**(1.-GAM)
           TERM2=(AREA*XT-VOLM)**(1.-GAM)
           PRKE3=ALPHA*((AREA*XT-VOLM)**GAM)*PBART*1.E+6*
     +                (TERM1-TERM2)/(1.-GAM)
        ENDIF
C
C  MUZZLE VELOCITY CALCULATION
C
        PRKEM=PRKE1+PRKE2+PRKE3
C
        PRVELM=SQRT(PRKEM*2./WTPR)
C
C  INCREASE IN MUZZLE VELOCITY OVER BASELINE
C
        VELINC=PRVELM-PRVELS
C
C  PERCENTAGE INCREASE IN MUZZLE VELOCITY
C
        VELPER=(VELINC/PRVELS)*100.
```

```
C
C   PERCENTAGE INCREASE IN MUZZLE KE
C
          RKEPER=((PRKEM-PRKES)/PRKES)*100.
C
C   ENERGY BALANCE AT MUZZLE
C   GAS KE
C
          GASKE=(1./3.)*(WTCH/WTPR)*PRKEM
C
C   GAS INTERNAL ENERGY
C
          TERM3=(AREA*XM-VOLM)**GAM
          TERM4=(AREA*XT-VOLM)**GAM
          PBARM=(TERM4/TERM3)*PBART
C
          GASINT=PBARM*1.E+6*VOLTOT/(GAM-1.)
C
C   TOTAL ENERGY REQUIRED
C
          ENTOT=PRKEM+GASKE+GASINT+RLOSS
C
C   ELECTRICAL ENERGY NEEDED
C
          ELEC=ENTOT-CHEMEN
C
C   ELEC IN MJ
C
          ELECMJ=ELEC*1.E-6
C
C    ELECTRICAL  ENERGY  DELIVERED  TO PROJECTILE (ELECTRICAL
EFFICIENCY)
C
          ELECP=((PRKEM-PRKES)/ELEC)*100.
C
C   OUTPUT
C
          WRITE(14,201) XT
          WRITE(14,202) TEMP
          WRITE(14,203) PRKEM
          WRITE(14,204) GASKE
          WRITE(14,205) GASINT
          WRITE(14,206) PRVELM
          WRITE(14,207) VELPER
          WRITE(14,208) RKEPER
          WRITE(14,209) ELECMJ
          WRITE(14,210) ELECP
C
  200     FORMAT(' ** ADDITION OF ELECTRICAL  ENERGY  TO SOLID
PROPELLANT **
     +',/)
  201     FORMAT(/,'   ELEC  ENERGY  TERMINATION  POINT  (M)
=',F10.4)
  202     FORMAT(' TEMPERATURE AT EE TERMINATION (K) =',F10.1)
  203     FORMAT(' PROJECTILE KE MUZZLE (J) =',F15.1)
  204     FORMAT(' GAS KE MUZZLE (J) =',F15.1)
  205     FORMAT(' GAS INTERNAL ENERGY (J) =',F15.1)
  206     FORMAT(' PROJECTILE VELOCITY WITH EE (M/S) =',F10.2)
```

```
  207   FORMAT(' PROJECTILE VELOCITY % INCREASE =',F10.1)
  208   FORMAT(' MUZZLE KE % INCREASE =',F10.1)
  209   FORMAT(' ELECTRICAL ENERGY NEEDED (MJ) =',F10.2)
  210   FORMAT(' ELECTRICAL EFFICIENCY (%) =',F10.1)
C
C
C
        IF(I .EQ. 1) THEN
           IX=INT(XT)
           XT=REAL(IX)+0.5
           IF (XT .GT. XM) XT=REAL(IX)
        ELSE
           XT=XT-0.5
           IF (XT .LT. XEND) GOTO 500
        ENDIF
  100   CONTINUE
C
  500   STOP
        END
```

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